Parity doubling in the high baryon spectrum: near-degenerate three-quark quartets

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Abstract

We report on the first calculation of excited baryons with a chirally symmetric Hamiltonian, modeled after Coulomb gauge QCD (or upgraded from the Cornell meson potential model to a field theory in all of Fock-space) showing the insensitivity to chiral symmetry breaking. As has recently been understood, this leads to doubling between two hadrons of equal spin and opposite parity. As a novelty we show that three-quark Δ states group into quartets with two states of each parity, all four states having equal angular momentum J. Diagonalizing the chiral charge expressed in terms of quarks we show that the quartet is slightly split into two parity doublets by the tensor force, all splittings decreasing to zero high in the spectrum.

Our specific calculation is for the family of maximum-spin excitations of the Delta baryon. We provide a model estimate of the experimental accuracy needed to establish Chiral Symmetry Restoration in the high spectrum. We suggest that a measurement of masses of high-partial wave Δ resonances with an accuracy of 50 MeV should be sufficient to unambiguously establish the approximate degeneracy, and test the concept of running quark mass in the infrared.

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The idea of chiral symmetry restoration has been around for a while, for example parity doubling was examined for the proton in the context of the linear sigma model in [1]. By current ideas we believe that this restoration should occur for higher excitations. Glozman and collaborators [2, 3, 4, 5, 6, 7, 8] (see also [9]) have theoretically examined ($q\bar{q}$) mesons, and also shown marginal empirical evidence for chiral symmetry restoration in both meson and hadron spectra, that rekindles interest on intermediate energy resonances. Chiral symmetry restoration, or more precisely, Spontaneous Chiral Symmetry Breaking Insensitivity high in the spectrum, is established as a strong prediction of the symmetry breaking pattern of QCD, and such prediction in an energy region where little else can be stated, needs to be confirmed or refuted by experiment.

The baryon spectrum is a more difficult theoretical problem given the minimum three-body wavefunction (as opposed to only quark-antiquark for mesons) and in this paper we provide the necessary theoretical background to understand parity doubling, in agreement with a prior study by Nefediev, Ribeiro and Szczepaniak [10], and give the first model estimate of what the experimental target-precision should be. This should help quantify what "high enough" in the spectrum means, to assist experimental planning.

We customarily employ a truncation of Coulomb-gauge QCD by ignoring the Faddeev-Popov operator

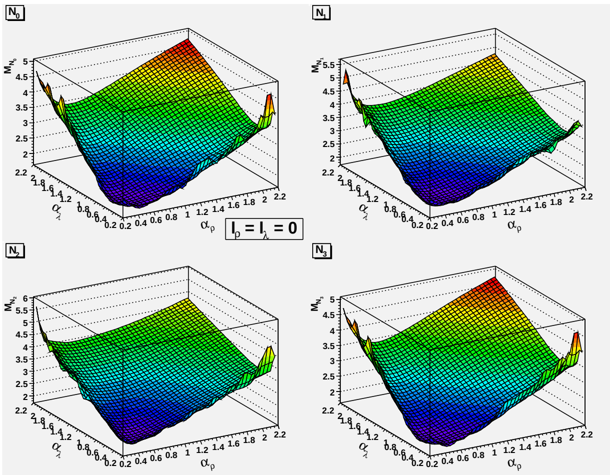

Figure 1: Variational minimum-energy search $E(\alpha_\rho, \alpha_\lambda)$ with a two-parameter family of functions. Best results are obtained when the (chiral-limit) pion wavefunction is rescaled and used to build the Jacobi-radial part of the Δ wavefunctions, $\sin\phi(k_\rho/\alpha_\rho)\sin\phi(k_\lambda/\alpha_\lambda)$. For maximum spin Δ states, $J = 3/2 + l_\rho$ the angular wavefunction before symmetrization is $Y_l^{m_l}(\hat{k}_\rho)$ (we set $l_\lambda = 0$ consistent with the variational approximation, but numerically symmetrize the spin-space wavefunction, which reintroduces it through exchanged-quarks).

and substituting the Coulomb kernel by its vacuum expectation value, that takes the usual linear plus Coulomb form. This can be seen as a field theory upgrade of the Cornell potential model. The Hamiltonian reads

$$H = -g_s \int d\mathbf{x}\Psi^\dagger(x)\alpha\cdot\mathbf{A}(x)\Psi(x) + Tr\int d\mathbf{x}(\mathbf{E}\cdot\mathbf{E} + \mathbf{B}\cdot\mathbf{B}) + \int d\mathbf{x}\Psi_q^\dagger(\mathbf{x})(-i\alpha\cdot\nabla + \beta m_q)\Psi_q(\mathbf{x}) + \frac{1}{2}\int d\mathbf{x}d\mathbf{y}\rho^a(\mathbf{x})V_L(|\mathbf{x}-\mathbf{y}|)\rho^a(\mathbf{y}) \quad (1)$$

with a strong kernel containing a linear potential V_L, with string tension $\sigma = 0.135\ GeV^2$, coupled to the color charge density $\rho^a(\boldsymbol{x}) = \Psi^\dagger(\boldsymbol{x})T^a\Psi(\boldsymbol{x}) + f^{abc}\mathbf{A}^b(\boldsymbol{x})\cdot\mathbf{\Pi}^c(\boldsymbol{x})$. In our past work we have solved the BCS gap equation to spontaneously break chiral symmetry. This model has the same chiral structure of QCD, satisfying the Gell-Mann-Oakes-Renner relation, the low-energy theorems for pion scattering[14] and allowing computations of static pion-nucleon observables[15]. We have employed it in studies of gluodynamics[16] shown at this workshop that agree with lattice gauge theory and are of qualitative phenomenological interest. In any case, these play a minor role in the topic of this article, as the decreasing of the splittings is dominated by chiral symmetry breaking alone. For a reduced baryon sector application we are going to perform two more simplifications. We employ only the V_L linear potential, and neglect all magnetic interactions. This makes the Δ-nucleon mass splitting too small, but does not affect the Δ spectrum much.

We truncate the Fock space variationally, as customary, to the $|qqq\rangle$ minimum wavefunction. Since radial excitations of this system compete with multiquark excitations, we concentrate instead on maximum angular-momentum excitations $J = 3/2 + l$. Chiral forces are too weak to compensate large centrifugal forces and can hardly maintain $l = 3$ or $l = 4$, so one hopes to reduce the molecular component by studying the ground state in each J-channel, so that the $|qqq\rangle$ correlation remains important high in the spectrum.

As a rule of thumb, one needs to keep in the Fock-space expansion $|qqq\rangle + |qqqq\bar{q}\rangle + |qqqg\rangle + \ldots$ as many states as will be competitive by phase space considerations, considering the quark and gluon dynamical mass gaps established by lattice and Dyson-Schwinger studies. When pentaquark correlations are more abundant than three-quark correlations (see figure 3) the typical quark momentum will be lower than extrapolated from the ground-state baryons, so that chiral symmetry restoration will not be quite so fast.

This puts pentaquark correlations above $2GeV$, with the exception of possible meson-baryon resonances (as the Goldstone bosons avoid the mass-gap). In any case it seems well established that three-quark correlations play an important role in baryon-phenomenology, so it is worth examining the effect of a chiral transformation on a three-quark variational wavefunction $|N\rangle = F_{ijk} B_i^\dagger B_j^\dagger B_k^\dagger |0\rangle$.

We proceed variationally and employ several types of wavefunctions, rational and Gaussian, but the lowest energy (binding the model's J-ground state from above by the Rayleigh-Ritz principle) is obtained by employing the chiral limit pion-wavefunction rescaled with two variational parameters in terms of Jacobi coordinates, $\sin\phi(k_\rho/\alpha_\rho)\sin\phi(k_\lambda/\alpha_\lambda) Y_l^{m_l}(\hat{k}_\rho)$. We have found the angular excitation in λ to be slightly higher in energy and neglect the correlation. Part of it though reenters the calculation upon (anti)symmetrizing the wavefunction, since quark exchange mixes the ρ and λ variables. A typical variational search is represented in figure 1. Table 1 presents the intradoublet splittings. The interdoublet splittings, as well as improved precision on our three-body variational Montecarlo method, will be given in an upcoming publication. As can be seen from the table, the model doublet splittings drop with the orbital angular momentum. This is easy to understand from the structure of the model Hamiltonian. The kernel for baryons is proportional to

$$F^*_{s_1 s_2 s_3}(\mathbf{k}_1, \mathbf{k}_2)\, U^\dagger_{k_1 s_1} U_{k_1+q\lambda_1}\, U^\dagger_{k_2 s_2} U_{k_2-q\lambda_2} \times F_{\lambda_1\lambda_2 s_3}(\mathbf{k}_1+\mathbf{q}, \mathbf{k}_2-\mathbf{q}) \quad (2)$$

that, upon becoming insensitive to the gap angle, $\sin\phi(k >> \Lambda_{QCD}) \to 0$, turns into

$$F^*_{s_1 s_2 s_3}\left(\delta_{s_1\lambda_1} + (\sigma\cdot\hat{k}_1 \sigma\cdot\widehat{k_1+q})_{s_1\lambda_1}\right)\cdot \left(\delta_{s_2\lambda_2} + (\sigma\cdot\hat{k}_2\sigma\cdot\widehat{k_2-q})_{s_2\lambda_2}\right) F_{\lambda_1\lambda_2 s_3}\ . \quad (3)$$

If instead of $F^*_{s_1 s_2 s_3}$ one substitutes its chiral partner $F^*_{s_1' s_2 s_3}(\sigma\cdot\hat{k}_1)_{s_1' s_1}$ (and the same for the ket), the two states are seen to be degenerate. Also apparent in Eq.(3) is the role of the tensor force in enforcing chiral cancellations.

Finally, the first computation of the parity doubling for baryons is presented in figure 2.

Let us now show that there are indeed two closely separated baryon doublets, slightly split by tensor forces. We find convenient to employ the gap angle instead of the quark mass

$$\sin\phi(k) \equiv \frac{M(k)}{\sqrt{M(k)^2 + k^2}}$$

Table 1: Experimental and computed doublet splittings. The entire quartet degenerates high in the spectrum, with the $+-$ parity doubling proceeding faster due to insensitivity to χSB and the interdoublet splitting decreasing slower, as they are due to the tensor force and dynamical. We give a preliminary calculation of the intradoublet splitting (parity degeneracy). From the decreasing theory splittings we deduce that an experimental measurement of the parity splitting $M_+ - M_-$ to an accuracy of 100, or better 50 MeV, should suffice to see the effect. Note that our excited splittings become compatible with zero within errors in the Montecarlo 9-d integral.

J	Exp. $M_+ - M_-$	Theory intradoublet
3/2	470(40)	450(100)
5/2	70(90)	400(100)
7/2	270(120)	50(100)
9/2	50(250)	200(100)
11/2	-	100(100)
13/2	-	100(100)

and the Dirac spinors can be easily parametrized as

$$U_{\kappa\lambda} = \frac{1}{\sqrt{2}}\begin{bmatrix} \sqrt{1+\sin\phi_\kappa}\chi_\lambda \\ \sqrt{1-\sin\phi_\kappa}\vec{\sigma}\cdot\hat{\kappa}\chi_\lambda \end{bmatrix} \quad (4)$$

$$V_{-\kappa\lambda} = \frac{1}{\sqrt{2}}\begin{bmatrix} -\sqrt{1-\sin\phi_\kappa}\vec{\sigma}\cdot\hat{\kappa} i\sigma_2\chi_\lambda \\ \sqrt{1+\sin\phi_\kappa} i\sigma_2\chi_\lambda \end{bmatrix}. \quad (5)$$

Substituting these spinors, and in terms of Bogoliubov-rotated quark and antiquark normal modes B, D, the chiral charge takes the form

$$Q_a^5 = \int \frac{d^3k}{(2\pi)^3} \sum_{\lambda\lambda' f f' c} \left(\frac{\tau^a}{2}\right)_{ff'} \Big(\cos\phi(k)\, (\sigma\cdot\hat{\mathbf{k}})_{\lambda\lambda'} \left(B^\dagger_{k\lambda f c} B_{k\lambda' f' c} + D^\dagger_{-k\lambda f c} D_{-k\lambda' f' c}\right) + \sin\phi(k)\, (i\sigma_2)_{\lambda\lambda'} \left(B^\dagger_{k\lambda f c} D^\dagger_{-k\lambda' f' c} + B_{k\lambda f c} D_{-k\lambda' f' c}\right)\Big)\ . \quad (6)$$

In the presence of Spontaneous Chiral Symmetry Breaking, $\sin\phi(k) \neq 0$, and the two terms in the second line are responsible for the non-linear realization of chiral symmetry in the spectrum. One can see this by applying the chiral charge on a hadron state to collect the same hadron state plus a pion. As in Jaffe, Pirjol and Scardiccio [11],

$$[Q_5^a, N_i^\pm] = v_0(\pi^2)\epsilon_{abc}\pi^c\Theta^b_{ij}N_j^\pm \ . \tag{7}$$

(Here, i and j are the chiral multiplet indices).
Eq. (7) is easy to derive because the $i\sigma_2$ matrix couples the quark-antiquark pair to pseudoscalar quantum numbers, so the terms in the second line of eq.(6) provide an interpolating field for the pion. In fact, if the vacuum is variationally chosen as the BCS ground state $|\Omega\rangle$ with $B|\Omega\rangle = 0$, $D|\Omega\rangle = 0$, $\sin\phi(k)$ then provides precisely the RPA pion wavefunction in the chiral limit, and the terms with $\sin\phi(k)$ become the RPA pion-creation operator.

If instead Chiral Symmetry was not spontaneously broken in QCD, $M(k) \simeq 0$ and $\sin\phi(k) \simeq 0$. As a consequence, it is obvious that the chiral charge would not change the particle content since the second line of eq.(6) would vanish, and the first line is made of quark and antiquark number operators. Then chiral symmetry would be linearly realized in Wigner-Weyl mode where hadrons come in degenerate opposite-parity pairs

$$[Q_5^a, N_i^+] = \Theta^a_{ij}N_j^-$$
$$[Q_5^a, N_i^-] = \Theta^a_{ij}N_j^+ \ .$$

The parity change follows from the $\sigma{\cdot}\hat{k}$ p-wave present in the first line of eq.(6).

In fact, the contemporary realization is that both phenomena are simultaneously realized in QCD. The vacuum is not annihilated by the chiral charge, forcing spontaneous symmetry breaking, but the mass gap angle has compact support and if, in a hadron, the typical quark momentum is high, as illustrated in figure 4, its wavefunction is insensitive to Chiral Symmetry Breaking. Therefore one asymptotically recovers degenerate Glozman parity doublets. We will in the following drop the isospin index.

If a given resonance is high enough in the spectrum so the quarks have a momentum distribution peaked higher than the support of the gap angle, as in figure 4, only the first line of Eq.(6) is active. $Q_5|N\rangle$ contains also three quarks, but one of them is spin-rotated from $B_{k\lambda}$ to $\sigma\cdot\hat{k}_{\lambda\lambda'}B_{k\lambda'}$. Successive application of the chiral charge spin-rotates further quarks, changing each time the parity of the total wavefunction. However the sequence of states ends since $\sigma\cdot\hat{k}\sigma\cdot\hat{k} = \mathbb{I}$. In fact, starting with an arbitrary such wavefunction, one generates a quartet

$$|N_0^P\rangle = \sum F^P_{ijk}B_i^\dagger B_j^\dagger B_k^\dagger|\Omega\rangle$$
$$|N_1^{-P}\rangle = \frac{1}{3}\sum F^P_{ijk}$$
$$\left(\left(\sigma\cdot\hat{\mathbf{k}}_i B^\dagger\right)_i B_j^\dagger B_k^\dagger + \text{ permutations}\right)|\Omega\rangle$$
$$|N_2^P\rangle = \frac{1}{3}\sum F^P_{ijk}$$
$$\left(\left(\sigma\cdot\hat{\mathbf{k}}_i B^\dagger\right)_i \left(\sigma\cdot\hat{\mathbf{k}}_j B^\dagger\right)_j B_k^\dagger + \text{ permutations}\right)|\Omega\rangle$$
$$|N_3^{-P}\rangle = \sum F^P_{ijk}$$
$$\left(\sigma\cdot\hat{\mathbf{k}}_i B^\dagger\right)_i \left(\sigma\cdot\hat{\mathbf{k}}_j B^\dagger\right)_j \left(\sigma\cdot\hat{\mathbf{k}}_k B^\dagger\right)_k |\Omega\rangle$$

that is the natural basis to discuss chiral symmetry restoration in baryons, through wavefunctions that are linear combinations $|N\rangle = \sum c_i|N_i\rangle$.

Because the Hamiltonian and the chiral charge commute, they can be diagonalized simultaneously.

The quartet then separates into two doublets connected by the chiral charge

$$\begin{aligned} Q_5(N_0 - N_2) &= N_1 - N_3 \\ Q_5(N_1 - N_3) &= N_0 - N_2 \\ Q_5(N_0 + 3N_2) &= 3(3N_1 + N_3) \\ Q_5(3N_1 + N_3) &= 3(N_0 + 3N_2) \end{aligned} \tag{8}$$

Since the quartet can be divided into two two-dimensional irreducible representations of the chiral group, (with different eigenvalues of Q_5^2, 1 and 9 respectively), the masses of the two doublets may also be different, and the interdoublet splitting becomes a dynamical question. However, the splitting within the doublet *must vanish* asymptotically. This is a prediction following from first principles-understanding of QCD alone. Should it not be borne experimentally, it would falsify the theory.

Of course, parity doubling is a property of a more general class of theories than QCD. Even for fixed (not running) quark mass, when the typical momenta are high enough $\langle \not{k} \rangle >> m$ in the kinetic energy, the effects of the quark mass are negligible. Parity doubling then comes down to whether the interaction terms are also chiral symmetry violating or not.

To round off this work, let us look ahead to what the highly excited spin spectrum may reveal. The J-dependence of the fall-off of the splittings $M_+ - M_-$ is an observable that reveals the underlying chiral theory. If precise data becomes available at ELSA or Jefferson Lab (note the EBAC, Excited Baryon Analysis Center effort[19]), in particular for the Δ_J with $J = 7/2, 9/2, 11/2$ parity doublets, one should be able to distinguish between the typical $1/\sqrt{l}$ fall-off for non-chiral models and the faster drop for chiral theories. (Higher yet in the spectrum, also the chiral theory may take on the $1/\sqrt{l}$ behavior due to the small remaining current quark mass that falls only logarithmically)[1].

Since the two doublets are closely degenerate, both positive and negative parity ground states will have a nearby resonance with identical quantum numbers. Given the width of those states, it is likely they will only be distinguished by very careful exclusive decay analysis. Meanwhile, if interpreted as only one resonance, their decay pattern will defy intuition.

It is also worth remarking that the spin-orbit interaction is very small in the low-lying spectrum, due to cancellations between scalar and vector potentials and the Thomas precession [20]. However, higher in the spectrum, the vector $\gamma_0\gamma_0$ potential comes forward, and it is known to present larger spin-orbit splittings than found to date. Therefore not all splittings in a given baryon shell will disappear alike: while parity splittings must decrease fast by chiral symmetry, other spin-orbit splittings will stay constant or even grow. This is demanded by a necessary cancellation between $L \cdot S$, centrifugal forces $l(l+1)$ and tensor forces. This has been explicitly shown for mesons in [21].

[1] Other authors have argued that flattening of the potential in a non-relativistic quark model for large distances due to screening (string-breaking) also leads to parity degeneracy [18]. We are preparing an additional paper that will provide the necessary detail for chiral models to distinguish them.

Table 2: Total width, exclusive pion-nucleon width and semiinclusive pion width (decay to one pion plus any other particles excluding pions) for the ground state Δ_J resonances. All units MeV. Data adapted from PDG[23] .

J^P	Γ	$\Gamma_{\pi N}$	$\Gamma_{\pi X}$
$\frac{3}{2}^+$	118(2)	118(2)	118(2)
$\frac{3}{2}^-$	300(100)	50(30)	190(90)
$\frac{5}{2}^+$	330(60)	42(18)	$< 80(20)$
$\frac{5}{2}^-$	350(150)	40(30)	-
$\frac{7}{2}^+$	285(50)	115(35)	170(30)
$\frac{7}{2}^-$	400(150)	30(20)	-
$\frac{9}{2}^+$	400(150)	30(20)	-
$\frac{9}{2}^-$	400(180)	35(25)	-
$\frac{11}{2}^+$	450(150)	50(40)	-
$\frac{11}{2}^-$	-	-	-
$\frac{13}{2}^+$	-	-	-
$\frac{13}{2}^-$	400(200)	20(12)	-
$\frac{13}{2}^+$	550(300)	30(25)	-

It has also been pointed out [8, 22, 10] that the pion decouples from the very excited resonances due to the falling overlap between the $\Delta *$ wavefunctions and $\sin\phi(k)$ (the pion wavefunction in the chiral limit). This might already be observable in the known widths for pion decays, that decrease even with larger phase space see table2. There are lattice calculations addressing low-excited baryons [24], but it is still a long way to go until highly excited states can be examined.

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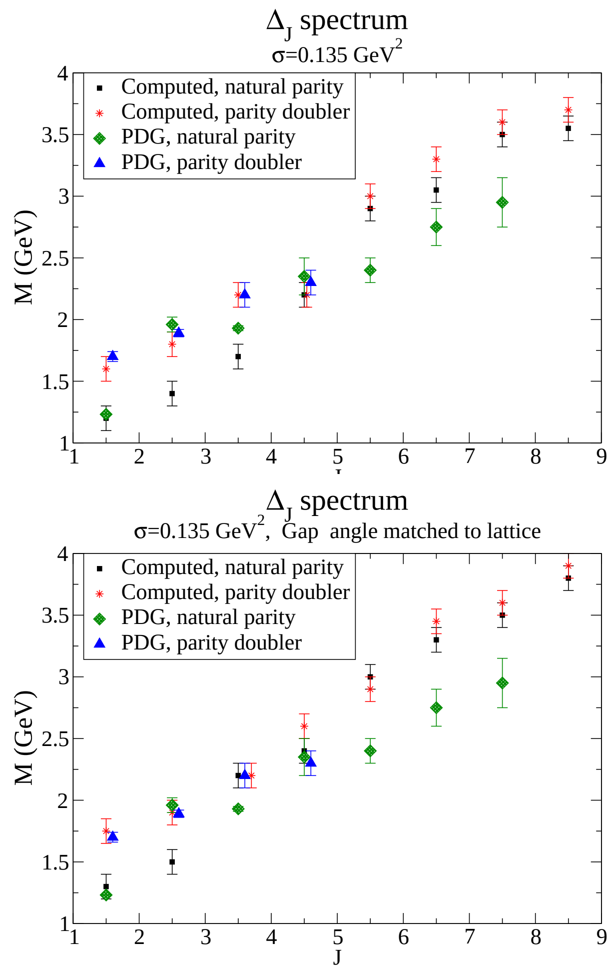

Figure 2: Parity doubling in the spin-excited Δ spectrum. Top: with infrared quark mass as calculated in the model (probably too low). Bottom: quark mass rescaled to fit Landau- gauge lattice data. The model clearly displays parity doubling. The experimental situation is still unclear, the degeneracy can be claimed for the 9/2 states alone, and the chiral partners higher in the spectrum are not experimentally known.

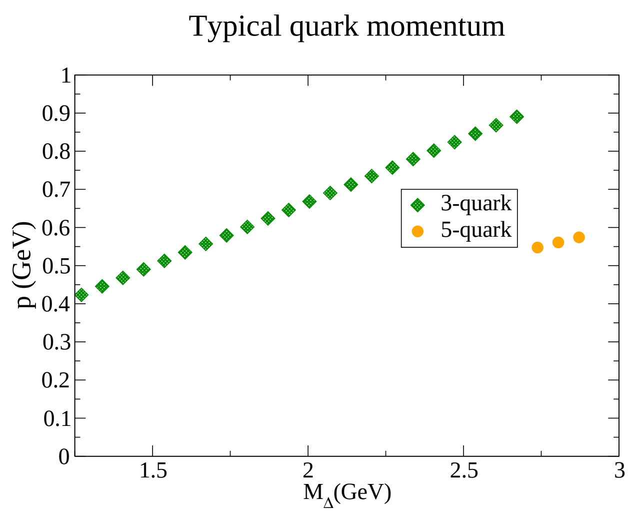

Figure 3: The typical momentum of a quark in a three-quark state is (by kinetic energy considerations alone, with a running mass-gap) $|k\rangle \propto M_{\Delta_J}$. Plotted is the typical momentum in a three quarks and five quark wavefunction. At the jump the phase space for five-quark states is larger, so it is more likely that a baryon of that mass is in a five-quark configuration, and the typical momentum is therefore smaller. Hence chiral symmetry restoration has to be somewhat slower than three-quark models would indicate.

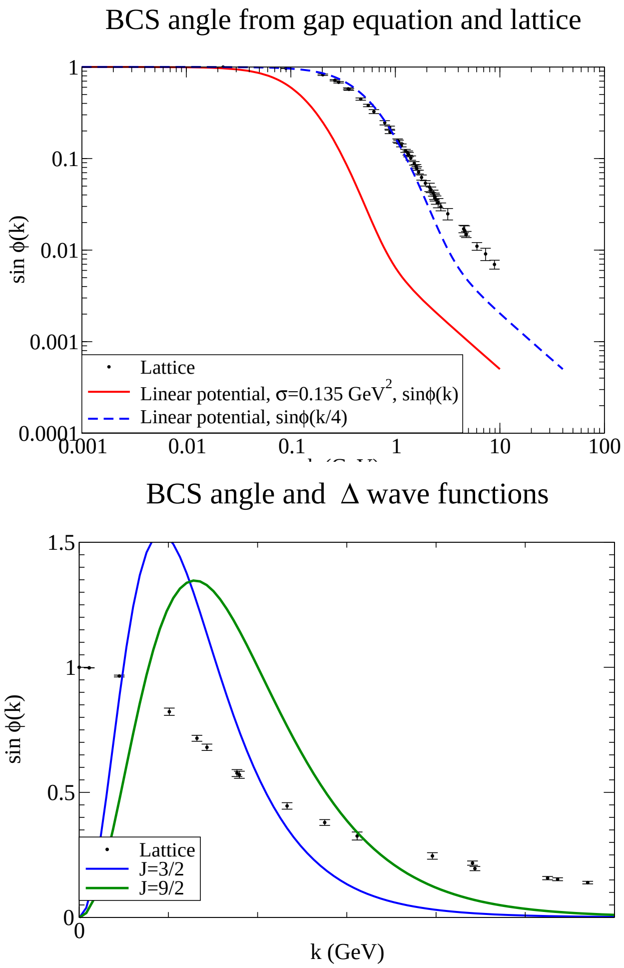

Figure 4: The sine of the gap angle $M(k)/\sqrt{(M(k)^2+k^2)}$ has limited support if the chiral-symmetry breaking quark mass remains of order Λ_{QCD} or less. Top: we show the running mass from a model computation for a linear potential with string tension $\sigma = 0.135\ GeV^2$, and its rescaling to match Landau-gauge data[12, 13] (no Coulomb-gauge lattice data for the quark mass is known to us). Bottom: Quark-momentum distributions for $\Delta_{3/2}$ and $\Delta_{9/2}$ with simple variational wavefunctions. The quark-momentum distribution for higher hadron resonances has smaller overlap with this gap angle, and therefore the quarks in those hadrons behave effectively as if they were massless. Hence they become insensitive to the gap angle, and chiral symmetry is restored in Wigner-Weyl mode with degenerate multiplets.